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## Depolarization of a $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ Polycrystalline Piezoelectric Energy-Carrying Element of Compact Pulsed Power Generator by a Longitudinal Shock Wave

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# DEPOLARIZATION OF A $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ POLYCRYSTALLINE PIEZOELECTRIC ENERGY-CARRYING ELEMENT OF COMPACT PULSED POWER GENERATOR BY A LONGITUDINAL SHOCK WAVE

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## ABSTRACT

A poled lead zirconate titanate  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  polycrystalline piezoelectric ceramic energy-carrying element of a compact explosive-driven pulsed power generator was depolarized by an explosive shock wave traveling along the polarization vector  $\mathbf{P}_0$ . We show that shock wave compression of a ferroelectric energy-carrying element at pressures of 1.5-3.8 GPa caused almost complete depolarization of the sample. The shock wave velocity in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  was determined to be  $3.94 \pm 0.27$  km/s. The electric charge stored in the ferroelectrics, due to their remnant polarization, is released during a short time interval, and can be transformed into pulsed power. Compact explosive-driven sources of primary power utilizing longitudinal shock wave depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  are capable of producing pulses of high voltage, with amplitudes up to 22 kV and peak powers up to 0.35 MW.

## I. INTRODUCTION

A wide range of modern devices relies on energy chemically stored in high explosives, propellants, metastable intermolecular composites, and high-energy-density nanocomposites. Explosive-driven electricity generators, considered the most effective modern compact sources of pulsed power, are one class of such devices [1]. Piezoelectric materials generate electric voltages when mechanically stressed, and are widely used in various electromechanical transducers. The class of piezoelectric materials exhibiting spontaneous polarization controlled by an external electric field is known as ferroelectric material, or ferroelectrics. In these materials, spontaneous polarization arises from bilateral symmetric potential minima between pairs of lattice sites. With the application of a high external electric field on a virgin ferroelectric crystal, all the spontaneously oriented domains formed by the sets of polarized dipoles become oriented parallel to

the applied electric field, reaching a state of saturation that characterizes the crystal as a single domain. Ferroelectric materials activated by an external electric field possess electrical, mechanical, and electromechanical properties resulting from their chemical formulation and the manufacturing process.

The design and performance of recently developed autonomous pulsed power sources utilizing electromagnetic energy stored in ferroelectric materials was described previously [2]. Compact explosive-driven generators based on shock wave depolarization of ferroelectric energy-carrying elements have been demonstrated to have reliable and controllable electrical operation [2]. The amount of electrical energy produced by a shock wave ferroelectric generator (FEG) is determined by the quantity of electric charge released in the electrical circuit of the generator during explosive operation. The efficiency of the device thus depends on the degree of depolarization of the ferroelectric energy-carrying element under the action of a shock wave. The complexity of the response of shock-compressed ferroelectrics, caused by the kinetics of domain reorientation, irreversible changes in material properties, specimen imperfections, etc., makes a consistent theoretical treatment of shock wave depolarization of the ferroelectric module a challenging problem [3]. This paper presents the results of an experimental investigation of the depolarization of a ferroelectric energy-carrying element within a compact FEG under the action of a shock wave generated by the detonation of a high explosive charge.

## II. EXPERIMENTAL

The test objects were commercial polycrystalline lead zirconate titanate  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  piezoelectric ceramic disks (supplied by EDO Corp.). Their parameters are as follows: density  $\rho_0 = 7.5 \times 10^3$  kg/m<sup>3</sup>, dielectric constant  $\varepsilon = 1300$ , Curie temperature 320 C, Young's modulus  $7.8 \times 10^{10}$  N/m<sup>2</sup>, piezoelectric constant  $d_{33} = 295 \times 10^{-12}$  C/N, and piezoelectric constant  $g_{33} = 25 \times 10^{-3}$  m<sup>2</sup>/C.

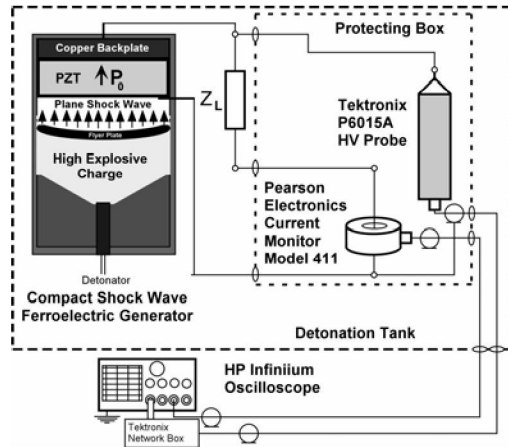
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A schematic diagram of the experimental setup is shown in Fig. 1. A shock wave was initiated at the front face of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk by a light aluminum impactor (flyer plate) (mass  $m = 5.1$  g) accelerated to high velocity by the detonation of desensitized RDX high explosives (Chapman-Jouguet state pressure of 22.36 GPa, and detonation velocity of 8.1 km/s). The mass of the RDX charge was 14 g. The shape of the aluminum flyer plate was determined in computer simulations so that flyer plate impact initiated a planar shock wave in the ferroelectric body. The air gap (acceleration path) between the flyer plate and the ferroelectric module's front face was 5 mm.

In the experiment, a ferroelectric disk was mounted on a copper backplate that provided mechanical impedance matching to minimize reflection of the stress wave when it reached the back face of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk. Silver contact plates were deposited on both faces of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk. Overall dimensions of the shock wave ferroelectric generators used in the experimental series did not exceed 50 mm. A detailed description of the devices can be found in [2].

The  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  module depolarization current and FEG output voltage waveforms were monitored with commercial current and voltage probes. Pearson Electronics current monitors, models 411 and 110, were used for measurement of pulse current. The voltage pulses were monitored using Tektronix P6015A and P6015 high voltage probes.



**Figure 1.** Schematic diagram of the experimental setup for investigation of the depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  energy-carrying elements of the FEGs.

Explosive experiments were performed at the Rock Mechanics and Explosive Research Center at the University of Missouri-Rolla. The commercial current and voltage monitors were enclosed in a protective steel container placed directly in the detonation tank. The distance between the current and voltage monitors and the output terminals of the compact generator was less than 35 cm. Hewlett-Packard Infinium oscilloscopes (bandwidth 500 MHz, 2 GSa/s) recorded the signals from the current and voltage monitors.

### III. RESULTS AND DISCUSSION

In this series of experiments, each  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk was poled parallel to its axis, to full remnant polarization values of  $P_0 = 30 \mu\text{C}/\text{cm}^2$ . The flyer plate provides longitudinal impact on the ferroelectric body so that the shock wave travels in a direction parallel to its polarization vector  $\mathbf{P}_0$ . Before flyer plate impact, the electric field in the ferroelectric sample is equal to zero because the dipole moment of the sample,  $P_0$ , obtained during the poling procedure, is compensated by surface charges. When a shock wave depolarizes the ferroelectric disk, free charges in the volume of the disk are redistributed. An electric field exists in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  and a pulsed electric potential (electromotive force) appears on the metallic contact plates of the ferroelectric module until a new equilibrium state is reached.

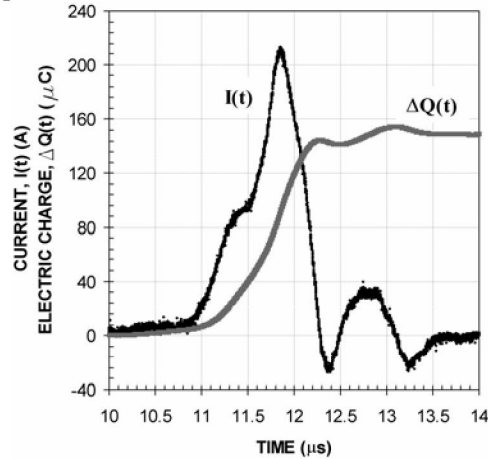
The pulsed electromotive force (EMF) causes a pulse of electric current,  $I(t)$ , to flow in the electrical circuit. Integration of the  $I(t)$  waveform from 0 to  $t$  gives the momentary value of the electric charge,  $\Delta Q(t)$ , released in the electrical circuit during explosive operation of the ferroelectric generator:

$$\Delta Q(t) = \int_0^t I(t) \cdot dt \quad (1)$$

The numerical value of the integral

$$\Delta Q_{\text{total}} = \int_0^{+\infty} I(t) \cdot dt \quad (2)$$

is equivalent to the total electric charge released by the ferroelectric energy-carrying element due to shock depolarization.



**Figure 2.** A typical waveform of the current pulse generated by an FEG containing a  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk ( $D = 26 \text{ mm}/h = 2.1 \text{ mm}$ ), and the corresponding electric charge,  $\Delta Q(t)$ , released due to the shock wave depolarization of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ .

We performed a series of experiments with  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disks of  $D = 26 \text{ mm}$  and different thicknesses,  $h = 0.65$  and  $2.1 \text{ mm}$ . A typical waveform of



the current pulse generated by an FEG containing a  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk of  $D = 26 \text{ mm}/h = 2.1 \text{ mm}$  is in Fig. 2. The load resistance and inductance were  $R_L(100 \text{ kHz}) = 0.2 \Omega$  and  $L_L(100 \text{ kHz}) = 0.53 \mu\text{H}$ , respectively. The current pulse amplitude was  $I(t)_{\max} = 213 \text{ A}$ , with full width at half maximum (FWHM) of  $0.5 \mu\text{s}$ .

Figure 2 also shows the evolution of the electric charge,  $\Delta Q(t)$ , released in the electrical circuit of the generator during shock wave action. The total charge released in the circuit in this experiment was  $\Delta Q_{\text{total}} = 157 \mu\text{C}$ .

The average value of the total electric charge released from  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disks under shock wave action in seven experiments of this series was  $\Delta Q_{\text{total}} = 154 \pm 17 \mu\text{C}$ .

The initial electric charge,  $Q_0$ , formed by the poling procedure and stored in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  energy-carrying elements, can be determined as follows:

$$Q_0 = P_0 \cdot A \quad (3)$$

where  $P_0$  is the remnant polarization of the ferroelectric sample and  $A$  is its area. Accordingly,  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disks with  $P_0 = 30 \mu\text{C}/\text{cm}^2$  and  $A = 5.3 \text{ cm}^2$  have  $Q_0 = 159 \mu\text{C}$ .

Based on our experimental results, the electric charge released by  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disks under shock wave action,  $\Delta Q_{\text{total}}$ , is almost equal to the charge stored in the ferroelectrics due to their remnant polarization,  $Q_0$ . This is direct evidence of practically complete depolarization,  $\Delta Q_{\text{total}} / Q_0 = 0.97$ , of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  due to the shock wave compression. Therefore, the physical effect of complete shock wave depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  ferroelectrics energy-carrying element of the FEG was detected experimentally.

Shock compression of materials results in simultaneous shock increase in the temperature of the material and shock mechanical compression of the crystal lattice. Therefore, the depolarization of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  ferroelectric sample may be due to the 180-degree switching of existing domains, nucleation and growth of new domains, or to a ferroelectric-paraelectric phase transition.

In the following manner, we calculated the shock pressure,  $P_{SW}$ , required to produce the experimentally-detected shock wave depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ . Assuming a perfectly elastic impact of an aluminum flyer plate of infinite diameter with an  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  element, also of infinite diameter, and assuming no plastic or fluidic behavior in either material at the moment of impact, the pressure acting on the front face of the ferroelectric disk,  $P_{SW}$ , can be estimated using the following equation [4]:

$$P_{SW} = (m \cdot s) / (\tau^2 \cdot A_{FP}) \quad (4)$$

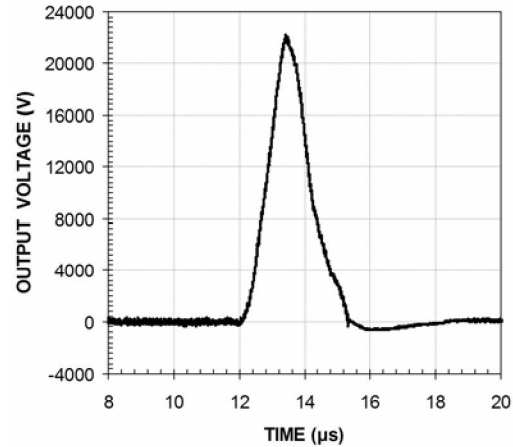
where  $m$  is the mass of the aluminum flyer plate,  $A_{FP}$  is the flyer plate area,  $s$  is the gap between the flyer plate and the ferroelectric energy-carrying element (acceleration path), and  $\tau$  is the time of free motion of the flyer plate preceding the impact.

To determine the time of free motion of the flyer plate, a series of experiments was performed with generators in

which the shock wave in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk was initiated by the direct action of explosive detonation (i.e., without a flyer plate). The time of free motion of the flyer plate,  $\tau = 4.7 \pm 0.3 \mu\text{s}$ , was determined from the shift in the time scale of the voltage pulses generated by the FEGs with a flyer plate (Fig. 1), versus FEGs utilizing the direct action of a detonation shock wave. This value is in good agreement with that obtained in another series of experiments performed with generators having transparent Lexan® bodies, in which free motion of the flyer plate was recorded using a high-speed Cordin 010-A framing camera.

Substituting a flyer plate mass  $m = 5.1 \text{ g}$ , acceleration gap  $s = 0.5 \text{ cm}$ , flyer plate area  $A_{FP} = 5 \text{ cm}^2$ , and  $\tau = 5.1 \pm 0.2 \mu\text{s}$  into Eq. (4) gives the pressure at impact of the flyer plate on the front face of the ferroelectric element,  $P_{SW} = 3.8 \pm 0.3 \text{ GPa}$ . This value is an upper bound, since the real impact situation will produce plastic behavior in the flyer, and the component diameters are not infinite. Relaxation waves from free surfaces and energy expended in the material by permanent deformation subtract from the pressure available at impact. In fact, experimental results have shown the flyer plate to have “splashed” on the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  surface, which typically shows little or no indication of deformation.

Exploring further the electrical output obtainable from compact explosive-driven FEGs, several designs of high-voltage and high-power FEGs have been studied. A typical waveform of an EMF pulse produced by a high-voltage FEG containing a  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk of  $D = 26 \text{ mm}/h = 6.5 \text{ mm}$  is in Fig. 3. The EMF pulse amplitude was  $U_g(t)_{\max} = 22.0 \text{ kV}$  with FWHM of  $1.1 \mu\text{s}$ .



**Figure 3.** Waveform of the pulsed EMF produced by a shock wave ferroelectric generator containing a  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk of  $D = 26 \text{ mm}/h = 6.5 \text{ mm}$ .

The load impedance in these high-voltage experiments was  $100 \text{ M}\Omega$ , therefore the current in the electrical circuit of the generator was negligibly small (less than  $3 \times 10^{-4} \text{ A}$ ). There was practically no interference with the electrical current flowing through the PZT module during shock wave induced depolarization. Moreover, transition

processes in the electrical circuit had no effect on the EMF pulse waveform generated by the PZT disk. In this mode of electrical operation, the increase in the EMF pulse from zero to its maximum value was the direct result of the depolarization of the ferroelectric energy-carrying element due to shock wave action. The EMF pulse risetime corresponded to the shock front propagation time through the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk thickness,  $h$ , and the velocity of the shock wave front could be determined utilizing the following relationship:

$$U_S = h/\tau_f \quad (5)$$

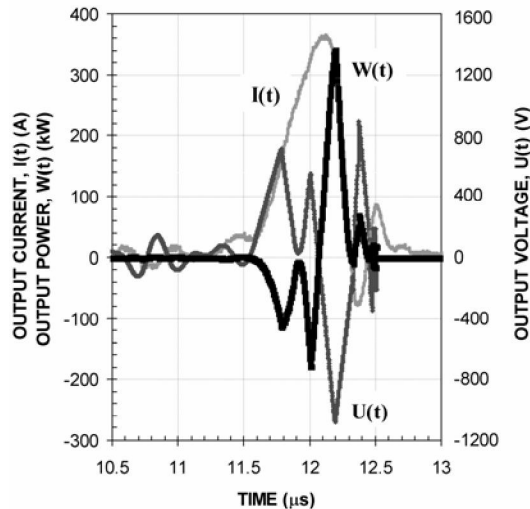
where  $\tau_f$  is the time of increase of the EMF pulse from zero to its maximum value. Accordingly, the shock wave velocity in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  was determined to be  $U_S = 3.94 \pm 0.27$  km/s.

The basic equation for shock wave pressure in condensed matter [4],

$$P_{SW} = \rho_0 \cdot U_S \cdot U_P \quad (6)$$

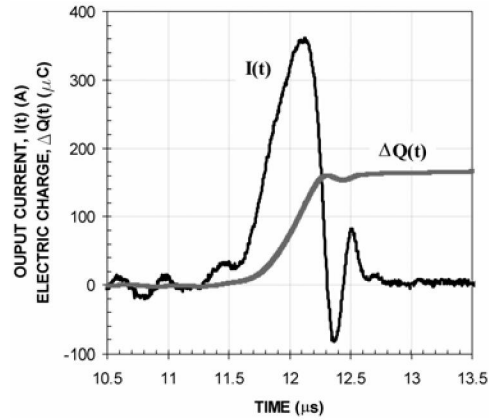
allows one to obtain the pressure in a shock-compressed body (here  $\rho_0$  is the density of material before shock action and  $U_P$  is the particle velocity). The particle velocity in the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  samples, corresponding to the shock wave velocity determined from the Hugoniot for  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  [5-7];  $U_P = 0.050 \pm 0.004$  km/s. The pre-shocked density of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  is  $7.5 \times 10^3$  kg/m<sup>3</sup>. Substituting these values for  $U_S$ ,  $U_P$  and  $\rho_0$  into (6) results in  $P_{SW} = 1.5 \pm 0.2$  GPa. The estimations of the pressure in the bulk of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  (1.5 GPa) and at the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ /flyer plate interface (3.8 GPa) upon impact are the lower and upper bounds of the pressure generated in ferroelectric modules.

The shock-induced electrical pulses produced by a high-power FEG containing a  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  disk of  $D = 26$  mm/ $h = 0.65$  mm are shown in Fig. 4.



**Figure 4.** Waveforms of output power (black), voltage (dark gray), and current (light gray) produced by a high-power FEG.

The peak power generated by the FEG was  $W(t)_{max} = 0.35$  MW with FWHM of  $0.1 \mu\text{s}$ . The output current pulse waveform and the corresponding function of the electric charge released in the electrical circuit of the generator,  $\Delta Q(t)$ , are shown in Fig. 5.



**Figure 5.** Waveform of the current pulse generated by the FEG, and the corresponding function of the electric charge released due to shock wave depolarization of the  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  energy-carrying element.

The current pulse amplitude,  $I(t)_{max} = 360$  A with FWHM  $0.5 \mu\text{s}$ . The total electric charge released by the ferroelectric energy-carrying element due to the shock wave depolarization was  $\Delta Q_{total} = 165 \mu\text{C}$ .

## IV. SUMMARY

Effect of the complete shock wave depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  ferroelectrics was detected experimentally. Miniature primary power sources based on this effect were designed, built and tested. They are capable of producing  $0.35$  MW peak power pulses with FWHM of  $0.1 \mu\text{s}$ .

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